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Simulation of winter wheat evapotranspiration in Texas and Henan using three models of differing complexity

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ABSTRACT

Crop evapotranspiration (ET) is an important component of simulation models with many practical applications related to the efficient management of crop water supply. The algorithms used by models to calculate ET are of various complexity and robustness, and often have to be modified for particular environments. We chose three crop models with different ET calculation strategies: CROPWAT with simple data inputs and no calibrations, MODWht for intensive inputs and limited calibrations, and CERES-Wheat with intensive inputs and more calibrations for parameters. The three crop models were used to calculate ET of winter wheat (*Triticum aestivum* L.) grown at two experimental sites of China and US during multiple growing seasons in which ET was measured using lysimeter or soil water balance techniques. None of the models calculated daily ET well at either Bushland or Zhengzhou as indicated by high mean absolute differences (MAD > 1.1 mm) and root mean squared errors (RMSE > 2.0 mm). The three models tended to overestimate daily ET when measured ET was small, and to underestimate daily ET when measured ET was large. The fitted values of daily crop coefficients (K_c), calculated from daily ET and reference ET (ET_o), were very similar to those of Allen et al. (1998) [Allen, R.G., Pereira, S.L., Raes, D., Smith, M., 1998. Crop evapotranspiration guidelines for computing crop water requirements. Irrigation and drainage paper 56, Rome] although some K_c were overestimated ($\geq$1.0). Leaf area index (LAI) was poorly calculated by MODWht and CERES-Wheat, especially when using the Priestley–Taylor method to estimate potential ET (PET). Poor overall ET calculation of three models was associated with poorly estimated values of PET or ET_o, K_c and LAI as well as their interactions. Therefore, this suggested that considerable revisions and calibrations of ET algorithms of the three models are needed for the improvement of ET calculation.

1. Introduction

Crop evapotranspiration (ET) is an important factor in crop growth and yield. Its accurate estimation is an important path to the efficient management of water. Inaccurate estimates of ET can lead to poor assessment of crop stress and yield, and inefficient use of water. Of nearly 700 registered ecological models (Benz and Voigt, 1995; http://eco.wiz.uni-kassel.de/ecobas.html), most are mechanistic in that they are based on established scientific principles and describe a system using a mathematical understanding of component processes (France and Thornley, 1984; Lascano, 1991). Mechanistic models distinguish among different levels of knowledge and organization within a system (de Wit, 1970; Lascano, 1991), and typically join two levels of knowledge: one that is to be explained, and the other that provides the explanation. Component processes that most ET models incorporate include atmospheric evaporative demand (Penman, 1948; Jensen and Haise, 1963; Monteith, 1965; Priestley and Taylor, 1972; Doorenbos and Pruitt, 1977; Hatfield, 1990; Allen et al., 1998), crop growth and development (de Wit, 1970, 1978; France and Thornley, 1984; Rickman et al., 1996; McMaster, 1997; Ritchie et al., 1998), and the soil water balance (Lascano, 1991; Evett and Lascano, 1993; Stockle et al., 1994).

Models of ET and other ecological models differ in their complexity, simplifying assumptions, input requirements, and system boundaries. On the one hand, ET simulation can be very complex, contain many modules of the soil–water–plant–atmosphere system with large input requirements, and require site-specific calibration or validation. Conversely, models that attempt to cover too many aspects of the soil water balance and plant growth defeat their purpose, as C.T. de Wit wrote, because ''Such a program would be too large to be critically evaluated and to solve detailed problems that arise under field conditions'' (de Wit, 1978). In general, model complexity should be geared towards system components and boundaries, and the problem or phenomenon that the modeler is trying to understand.

An example of a relatively simple ET model is CROPWAT, developed by Smith (1992) principally for irrigation management. It has been used worldwide to estimate crop water use and optimize irrigation for about 30 crops. It is user-friendly, requires few inputs (Table 1), and has an easily interpreted output. An example of a more complex and mechanistic model is MODWht, which is the best-known model of the broader crop simulation framework MODCROP (Waldman and Rickman, 1996). MODWht was developed in semiarid eastern Oregon by Rickman et al. (1996) to simulate daily growth and development of winter wheat with minimal local calibration. It computes the time of appearance and size of each plant part on a daily time step from germination to grain ripening as a linear function of cumulative degree days, using a base temperature of 0 °C. The program was designed to be modular so that it could be easily understood and modified. Required inputs for MODWht are shown in Table 2.

Table 1 – Inputs required by CROPWAT

Parameter or variable	Unit
Location data	
Country	
Station	
Latitude	°
Longitude	°
Altitude	m
Monthly climatic data	
Mean maximum temperature	°C
Mean minimum temperature	°C
Mean air humidity	%
Mean wind speed	$m\ s^{-1}$
Precipitation	mm
Soil data	
Total available soil water	$mm\ m^{-1}$ depth
Maximum rain infiltration rate	$mm\ d^{-1}$
Maximum rooting depth	m
Initial soil water depletion	%
Crop data	
Planting date	day/month
Harvesting date	day/month
Irrigation	
Date	day/month
Amount	mm

Table 2 – Inputs required by MODWht

Parameter or VARIABLE	Variable name	Unit
Site data		
Site and year		
Beginning crop day	begday	d
End of crop day	endday	d
Latitude	deg	°
Elevation of soil surface	elev	m
Beginning year of climate data	begyr	year
Yearly crop data		
Planting date	seeday	day
Planting depth	pldpth	cm
Row space	rwspg	cm
Planting rate	plrate	$kg\ ha^{-1}$
Percent germination	pcgerm	%
Kernel size	krnls	$No.\ kg^{-1}$
Phyllochron	phlcrn	degree days $leaf^{-1}$
Climatic data		
Daily maximum temperature	T_{max}	°C
Daily minimum temperature	T_{min}	°C
Daily solar radiation	Ra	$MJ\ m^{-2}\ d^{-1}$
Daily precipitation	Prec	mm
Daily air humidity	Relhum	%
Soil data		
Depth	Depth	cm
Volumetric water content	Wat	
Field capacity	Sat	$cm^3\ cm^{-3}$
Permanent wilting point	Wlt	$cm^3\ cm^{-3}$
Bulk density	BulkD	$g\ cm^{-3}$
N content	N	ppm
Nitrogen application		
Month		
Day of year		d
Amount		$kg\ ha^{-1}$
Irrigation		
Day of year		day
Amount		mm

CERES-Wheat, one of the most complex models, was developed by USDA-ARS to simulate wheat growth, development, and yield as affected by such factors as cultivar, planting density, climate, soil water, and nitrogen availability (Ritchie and Otter, 1985). CERES-Wheat has been used and evaluated extensively in many different parts of the world (Steiner et al., 1991; Porter et al., 1993; Touré et al., 1995; Jamieson et al., 1998). In response to user feedback, it has been occasionally modified and updated (IBSNAT, 1988; Ritchie et al., 1998). Recently, CERES-Wheat has been used to analyze effects of various policy questions, e.g. those related to global warming (White, 2003). The model's inputs are shown in Table 3.

With a view towards de Wit's (1978) restatement of Occam's razor: ''One should not increase, beyond what is necessary, the number of entities required to explain anything'', the objective of this study was to compare and evaluate ET estimation of winter wheat in two very different environments – Henan province in China and the Texas High Plains – using three crop models of different complexity, namely CROPWAT, MODWht, and CERES-Wheat.

Table 3 – Inputs required by CERES-Wheat

Parameter or variable	Variable name	Unit
Location data		
Latitude	LAT	°
Longitude	LONG	°
Planting data		
Sowing date	PDATE	year + DOY
Plant population	PPOP	plants m^{-2}
Sowing depth	PLDP	cm
Climatic data		
Date	DATE	year + DOY
Daily maximum temperature	TMAX	°C
Daily minimum temperature	TMIN	°C
Daily solar radiation	SRAD	MJ m^{-2} d^{-1}
Precipitation	RAIN	mm
Wind speed	WIND	m s^{-1}
Dew point	DEWP	°C
Soil basic data		
Soil albedo	SALB	
Evaporation limit	SLU1	cm
Drainage rate	SLDR	
Runoff curve number	SLRO	
Layer thickness	SLDP	cm
Lower limit of plant-extractable water	SLLL	cm^3 cm^{-3}
Upper limit, drained	SDUL	cm^3 cm^{-3}
Upper limit, saturated	SSAT	cm^3 cm^{-3}
Root growth factor	SRGF	0–1
Bulk density	SBDM	g cm^{-3}
Organic matter	SLOC	%
Soil initial data		
Layer	ICBL	cm
Soil water content	SH_2O	cm^3 cm^{-3}
NH_4 content	SNH_4	g N Mg^{-1}
NO_3 content	SNO_3	g N Mg^{-1}
Irrigation data		
Irrigation day	IDATE	Year + DOY
Irrigation amount	IRVAL	mm
Fertilizer application		
Date	FDATE	Year + DOY
Depth	FDEP	cm
Amount	FAMN	kg ha^{-1}
Wheat genotype coefficients		
Variety name		
Description of vernalization	P1V	
Description of photoperiod responses	P1D	
Relative grain filling duration	P5	
Kernel numbers per unit weight of stem	G1	g^{-1}
Kernel filling rate under optimum conditions	G2	mg d^{-1}
Dry weight when elongation ceases	G3	g
Phyllochron interval	PHINT	degree days

2. Model calculation of crop ET

CROPWAT calculates daily reference evapotranspiration (ET_o) using the FAO version of the Penman–Monteith equation (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \times 900/(T_a + 273) \times u_2 \times (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where Δ is the slope of the saturation vapor pressure/temperature relationship (kPa °C), R_n is net radiation (MJ m^{-2} d^{-1}), G is soil heat flux (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa $°C^{-1}$), T_a is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), and $e_s - e_a$ is the saturation vapor pressure deficit (kPa). Crop ET is then simply estimated by multiplying ET_o by an empirical crop coefficient (K_c) which is provided by CROPWAT for different growth stages:

$$ET = ET_o \times K_c. \quad (2)$$

MODWht uses the Jensen–Haise equation (Jensen and Haise, 1963; Jensen and Heermann, 1970; Jensen et al., 1990) to calculate potential evapotranspiration (PET) from

$$PET = \frac{C_t \times (T_a - T_x) \times R_n}{0.0171} \quad (3)$$

where C_t is a temperature coefficient; T_a is the average air temperature (°C); T_x is a vapor pressure and elevation term (°C); and R_n is net radiation (MJ m^{-2} day^{-1}). Soil water evaporation (Evap) is calculated from

$$Evap = Evapsoil \times PET \quad (4)$$

where Evapsoil is an empirical coefficient that changes as a function of soil surface water (mm). Transpiration (Transp) (mm) is calculated from

$$Transp = Cropcf \times PET \quad (5)$$

where Cropcf is a crop coefficient related to leaf area by the equation

$$Cropcf = \frac{LAI}{3}. \quad (6)$$

The value of leaf area index (LAI) is calculated from modules that calculate photosynthesis and its partitioning based on the development stage, which is temperature-driven as a linear function of cumulative degree days. ET is then calculated by summation:

$$ET = Evap + Transp. \quad (7)$$

CERES-Wheat can use either the Priestley–Taylor (R) (1972) equation to calculate PET, or the FAO version of the Penman equation (P) (Doorenbos and Pruitt, 1984) to calculate ET_o. When using the R equation (1972), CERES-Wheat calculates albedo from calculated growth stage and LAI values, and uses temperature-dependent constants to account for the effects of radiation, unsaturated air, and advection on PET (Ritchie and Godwin, unpublished; Ritchie, 1972). The PET is calculated from the equilibrium evaporation (EEQ) of Priestley and Taylor (1972):

$$PET = EEQ \times 1.1 \quad \text{if } 5\,°C \le T_{max} \le 35\,°C; \quad (8)$$

$$PET = EEQ \times [(T_{max} - 35) \times 0.05 + 1.1] \quad \text{if } T_{max} > 35\,°C; \quad (9)$$

$$PET = EEQ \times 0.01 \times e^{[0.18\times(T_{max}+20)]} \quad \text{if } T_{max} < 5\,°C. \quad (10)$$

In these equations, T_{max} is maximum daily air temperature, and EEQ is calculated from solar radiation, average air temperature, and albedo (Priestley and Taylor, 1972). When using the P method, CERES-Wheat calculates ET_o from the FAO version of the Penman equation (Doorenbos and Pruitt, 1984), which requires the additional inputs of wind speed and vapor pressure deficit.

CERES-Wheat partitions PET (or ET_o) into potential soil water evaporation (EOS) and potential crop transpiration (EOP) by estimating the fraction of solar energy reaching the soil surface from a negative exponential function of LAI ≥ 1 (Jones et al., 2003):

$$\mathrm{EOS} = \frac{\mathrm{PET}}{1.1} \times e^{(-0.4\times \mathrm{LAI})}. \tag{11}$$

For LAI < 1,

$$\mathrm{EOS} = \mathrm{PET} \times (1 - 0.43 \times \mathrm{LAI}). \tag{12}$$

Actual soil water evaporation is calculated by determining whether evaporation is limited by soil properties or atmospheric demand (Ritchie, 1972). If actual evaporation is less than EOS, the difference is added to EOP to account for increased canopy heat load due to a dry soil surface (Ritchie, 1972).

To calculate EOP, LAI values are also used. For LAI ≤ 3,

$$\mathrm{EOP} = \frac{\mathrm{PET} \times \mathrm{LAI}}{3}, \tag{13}$$

and for LAI ≥ 3,

$$\mathrm{EOP} = \mathrm{PET}, \tag{14}$$

Reducing EOP to actual transpiration requires a calculation of root water absorption (Ritchie and Godwin, unpublished). Actual transpiration can thus be limited by low solar radiation or cool ambient temperatures for low atmospheric demand, low canopy LAI, or low soil water (Jones et al., 2003).

3. Materials and methods

Experimental ET data were obtained from the USDA-ARS, Conservation and Production Research laboratory, Soil and Water Management Research Unit at Bushland, Texas (35°11′N; 102°06′W; 1170 m altitude); and the Institute of Henan Meteorology, Zhengzhou, Henan province in China (34°28′N; 112°50′E; 45 m altitude). At Bushland, irrigated winter wheat was grown during three growing seasons: 1989–1990, 1991–1992 and 1992–1993. At Zhengzhou, winter wheat was grown for one growing season only, 2000–2001. At the two experimental sites, winter wheat was planted from late September to October, and harvested from later May to early July. The growing period wheat at Henan was shorter than at Texas by at least 38 d, and the anthesis and maturity occurring time was also earlier. Plant population at both sites varied from 131 to 220 m^{-2}. Nitrogen fertilizer ranged from 80 to 130 kg N (Table 4).

Details of winter wheat phenology, LAI, weather, soil water content and irrigation management during the three growing seasons at Bushland were given by Evett et al. (1994) and Howell et al. (1996). The highest LAI of winter wheat reached 3.65 during 1989–1990, 7.07 during 1991–1992, and 4.18 during 1992–1993. The soil at Bushland is a Pullman clay loam (fine, mixed, superactive, thermic Torretic Paleustolls). Daily ET was measured by weighing lysimeters that were 3-m by 3-m by 2.4-m deep and located in the center of square 4.4-ha plots (Evett et al., 1994). Lysimeter mass was measured every 6 s and half-hourly means were recorded to calculate daily ET. Lysimeter accuracy was 0.05 mm of water (Howell et al., 1995b).

The soil at Zhengzhou is a sandy loam. Gravimetric water content of nine layers from 0.15 to 2.1 m depth was determined using hand augers at 10–20 d intervals after planting. Soil gravimetric water content was converted to soil volumetric water content using soil bulk density values (Zhu, personal communication, 2001). Evapotranspiration at Zhengzhou was calculated using the soil–water balance equation:

$$\mathrm{ET} = P + \mathrm{SW} + I \tag{15}$$

where P is the precipitation (mm), SW is the change of soil storage water between measurements (mm), and I is the amount of irrigation (mm). Drainage below the root zone and runoff were assumed to be negligible based on soil profile properties, precipitation and experimental management at Zhengzhou. Mean daily ET was calculated by dividing ET by the number of days between two soil water content measurements. Dates of anthesis and maturity were recorded.

The CROPWAT model does not require calibration, but some parameters, such as wheat growth stage data, need to be determined before the model is run. The MODWht model lacks ranges of genetic-related parameters for different cultivars, but phyllochron can be modified by cultivar description. Calibration of CERES-Wheat involved determination of six genetic coefficients or different varieties. The software GENCAL was used to estimate the genetic coefficients with the corresponding descriptions of varieties and local climate

Table 4 – Agronomic information during different growing seasons of winter wheat at Bushland, TX; Zhengzhou, China

Growing season	Cultivar	Planting date	Anthesis (DAP)	Maturity (DAP)	Plant population (no. m^{-2})	Fertilizer N (kg ha^{-1})	Grain yield (kg ha^{-1})
Bushland							
1989–1990	TAM 200	10 October 1989	16 May 1990 (216)	16 June 1990 (257)	190	130	4214
1991–1992	TAM 107	27 September 1991	8 May 1992 (221)	6 July 1992 (280)	193	110	6690
1992–1993	MESA	29 September 1992	13 May 1993 (225)	28 June 1993 (271)	131	80	6422
Zhengzhou							
2000–2001	Yumai-35	18 October 2000	20 April 2001 (182)	27 May 2001 (219)	220	120	6268

The DAP is the days after planting.

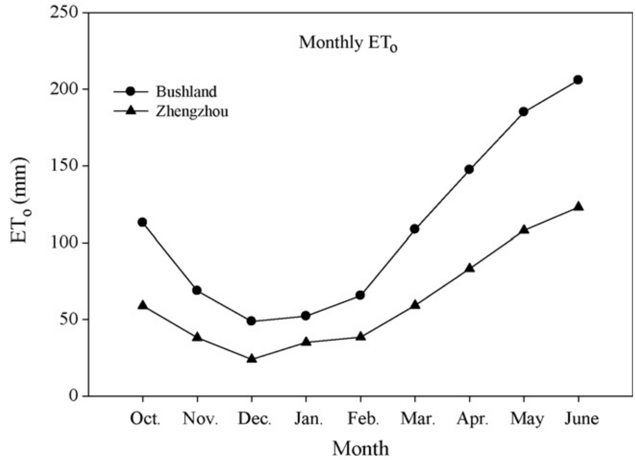

Fig. 1 – Monthly reference evapotranspiration (ET_o) during the growing season of winter wheat at the two experimental sites: Bushland, TX, and Zhengzhou, China, based on last 20 years' average monthly weather data.

(Hunt and Pararajasingham, 1993). The genetic coefficients were adjusted using the method of limited variables (Mavromatis et al., 2001).

We also used daily weather data from each site and the software program REF-ET (Allen, 1999) to calculate ET_o, then compared residuals of calculated daily ET_o (or PET) to ET_o results estimated from REF-ET (Fig. 6). In this study, the REF-ET version of the Penman–Monteith equation was viewed as a standard (or widely accepted model) because it has proven to be robust for ET_o calculations under different climates and locations (Allen et al., 1989; Steiner et al., 1991; Howell et al., 1996) although it could underestimate ET_o at some extreme conditions such as hot summers (Lascano and van Bavel, 2007). Daily weather data included maximum and minimum ambient air temperatures, solar radiation, relative humidity, and wind speed measured at 2 m height at the experimental sites. Daily PET, based on the FAO Penman–Monteith equation (Allen et al., 1998), was calculated with the software program REF-ET (Allen, 1999). Daily K_c is calculated through measured ET divided by ET_o using REF-ET.

Several statistical parameters were used to compare ET calculated results to measured values and among the three models. The statistical analysis software SAS was used for linear regression analysis (SAS Institute, 1999). The mean absolute difference (MAD) and root mean square error (RMSE) were calculated from

$$\text{MAD} = \frac{1}{n}\sum_{i=1}^{n}(|S_i - M_i|) \quad (16)$$

and

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \quad (17)$$

where S_i and M_i represent calculated and measured values, respectively, and n is the number of samples. While MAD reflects the absolute bias between the calculated and measured values, RMSE quantifies the dispersion between calculated and measured data.

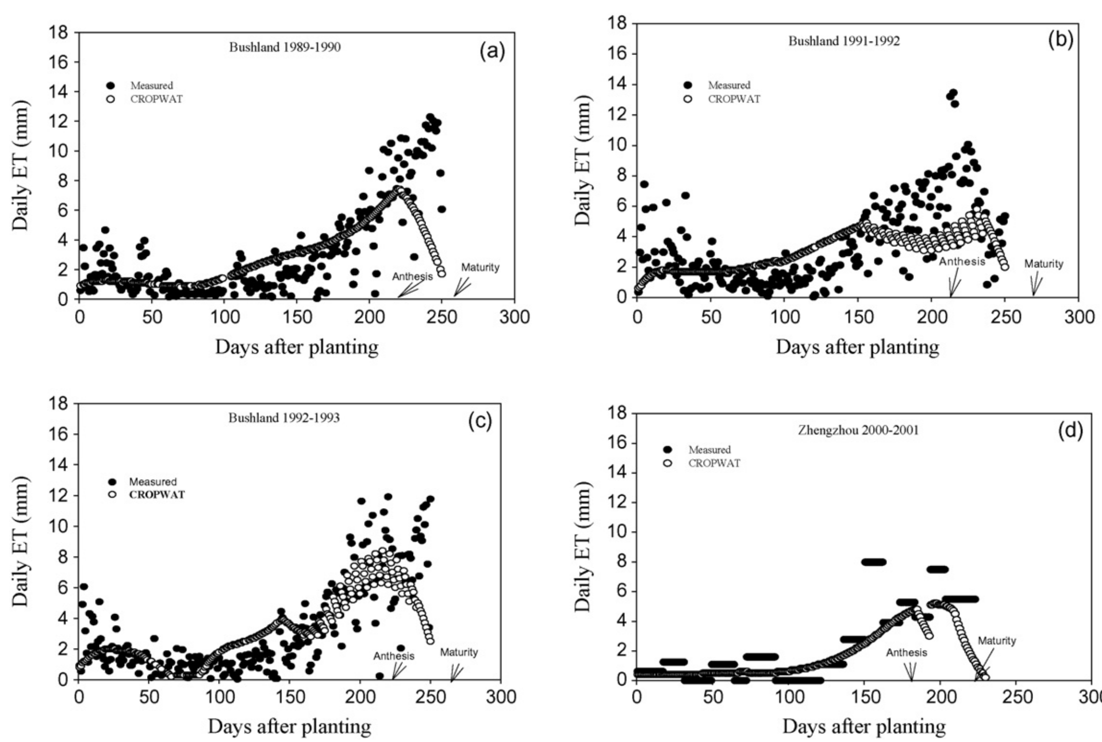

Fig. 2 – Comparison of calculated daily ET by CROPWAT using the FAO Penman–Monteith equation and measured daily ET for growing seasons of 1989–1990 (a), 1991–1992 (b), 1992–1993 (c) at Bushland, TX, and 2000–2001 (d) at Zhengzhou, China.

The index of agreement (D) (Willmott, 1981) was also used for model comparison and evaluation.

$$D = 1 - \frac{\sum_{i=1}^{N}(S_i - M_i)^2}{\sum_{i=1}^{N}(|S_i'| + |M_i'|)^2}. \qquad (18)$$

In Eq. (18), $S_i' = S_i - \bar{M}$ and $M_i' = M_i - \bar{M}$. The value of D, which ranges from 0 to 1, reflects the degree to which the measured variable is accurately estimated by the calculated variable. The measured variable is estimated perfectly when the value of D is 1. Conversely, the measured variable is estimated poorly when D is zero.

4. Results and discussion

4.1. *Long-term monthly PET at Bushland and Zhengzhou*

Mean monthly ET_o during winter wheat growing seasons calculated with the Penman–Monteith equation (Allen et al., 1998) using monthly weather data for the last 20 years (Fig. 1). Total ET_o at Bushland (994.5 mm) during the whole winter wheat growing season is higher than at Zhengzhou (567.5 mm) by 427 mm. This suggests that atmospheric evaporative demand at Bushland is considerably greater than at Zhengzhou. One would therefore generally expect daily ET to be much higher at Bushland than at Zhengzhou, partly due to much higher wind speed and vapor pressure deficit (Howell et al., 1995a).

4.2. *Daily ET calculation*

CROPWAT often underestimated ET on days with high measured values by 0.5–5 mm during the first 50 days after planting (DAP), and generally overestimated it by 0.2–2 mm from 100 to 150 DAP during all three growing seasons at Bushland (Fig. 2a–c). Daily ET at Bushland was seriously underestimated from sowing to 15 DAP, and again after 200 DAP. The highest underestimated daily ET can be over 2 mm. This could be due to the higher atmospheric water demand associated with high wind speed at Bushland and unsuitable PET or ET_o calculation parameters as suggested by Evett et al. (1994), and the earlier LAI degreasing during late growing stages. At Zhengzhou, CROPWAT calculated daily ET fairly well before 150 DAP (Fig. 2d), but underestimated it during the late growing season (after 150 DAP), as it had done for wheat grown at Bushland.

MODWht generally tended to underestimate daily ET at both Bushland and Zhengzhou (Fig. 3a–c). As with CROPWAT, calculated daily ET was considerably lower than measured daily ET (>2 mm) for a number of days with high evaporative demand before 50 DAP and after 170 DAP in the 1989–1990 and 1992–1993 growing seasons at Bushland (Fig. 3a and c), and around 150 and 200 DAP in the 2000–2001 season at Zhengzhou (Fig. 3d).

Daily ET calculated by CERES-Wheat (R) (Fig. 4) and CERES-Wheat (P) (Fig. 5) fit measured daily ET well before 150 DAP, but CERES-Wheat (R) seriously underestimated daily ET late in the

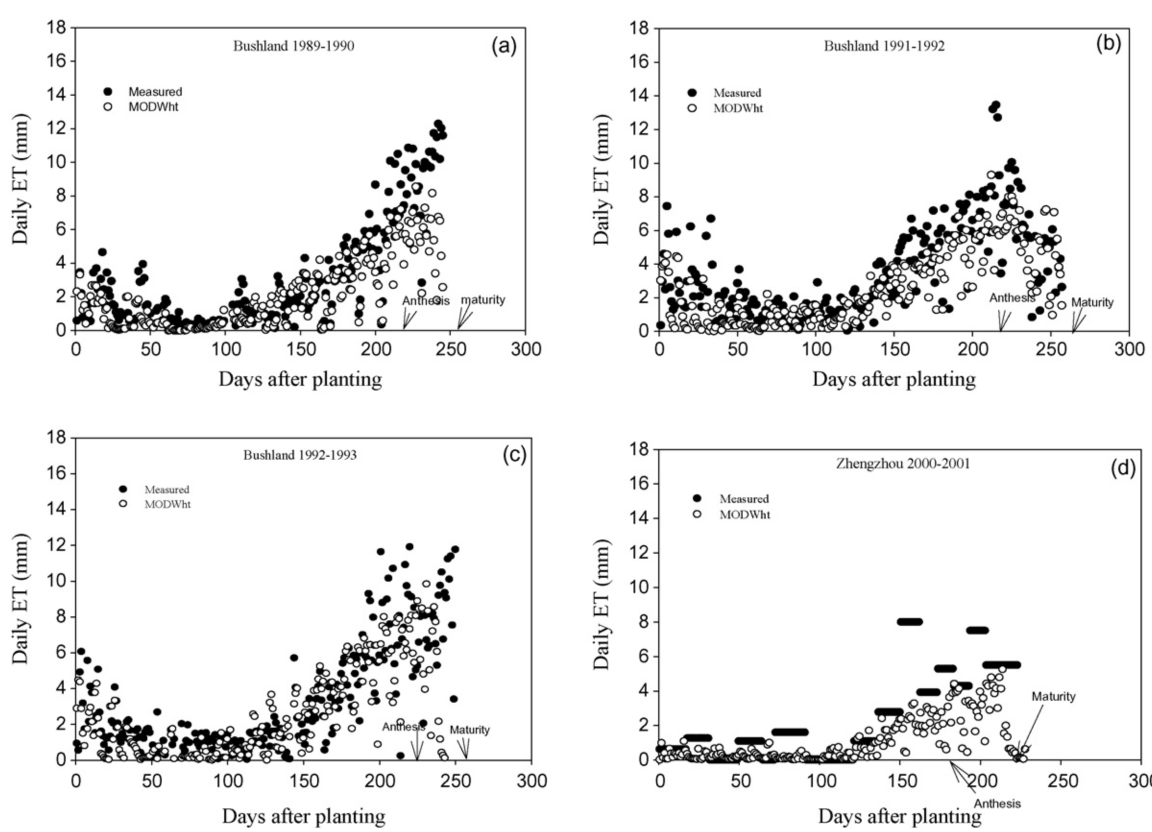

Fig. 3 – Comparison of calculated daily ET by MODWht using the Jensen–Haise equation and measured daily ET for growing seasons of 1989–1990 (a), 1991–1992 (b), 1992–1993 (c) at Bushland, TX, and 2000–2001 (d) at Zhengzhou, China.

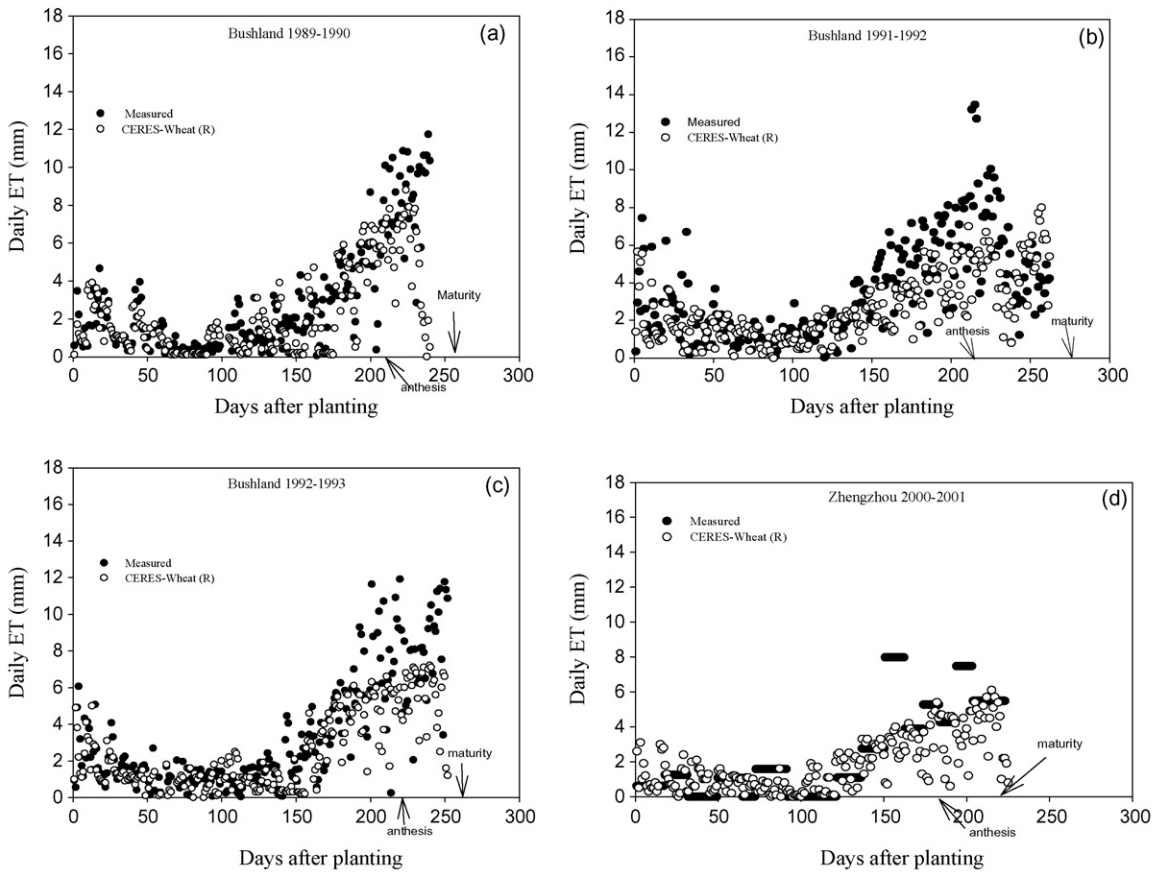

Fig. 4 – Comparison of calculated daily ET by CERES-Wheat (R) using the Priestley–Taylor equation and measured daily ET for the growing seasons of 1989–1990 (a), 1991–1992 (b), 1992–1993 (c) at Bushland, TX, and 2000–2001 (d) at Zhengzhou, China.

growing season at both sites. This was especially so on days at Bushland for which measured daily ET was $\geq$6 mm. CERES-Wheat (P) was better able to calculate daily ET during such periods and in some cases (see 1989–1990 for Bushland) actually over-estimated daily ET by several mm.

Simple linear regression analysis indicated that all three models tended to overestimate daily ET when measured ET was small, and to underestimate daily ET when measured ET was large (all intercepts >0, $P < 0.05$; all slopes < 1, $P < 0.05$) (Table 5). All three models had high MAD (>0.8) and RMSE (>1.7) for daily ET calculation. Although D values of CROPWAT and MODWht models were >0.80, taken overall, the analytical results suggested that none of the models could calculate daily ET very well at either site.

4.3. Daily ET_o and PET calculation

Appropriate ET_o (or PET) calculation is critical to all three models' simulations of daily ET, as stated in Eq. (1) for CROPWAT, Eqs. (3)–(7) for MODWht, and Eqs. (8)–(14) for CERES-Wheat. Many values of daily ET_o calculated by CROPWAT at Bushland were higher than REF-ET values during the 1991–1992 season, but compared well during other seasons and sites (Fig. 6). CROPWAT uses the same Penman–Monteith equation to calculate ET_o, but uses monthly means for weather input data. In contrast, MODWht and CERES-Wheat (R) tended to underestimate PET compared to REF-ET. During later growth stages (after 100 d), CERES-Wheat (P) overestimated ET_o for the 1989–1990 and 1992–1993 seasons at Bushland, and the 2000–2001 season at Zhengzhou. However, it tended to underestimate ET_o during the 1991–1992 season at Bushland. Additionally, high ET_o residual values were measured during the later parts of 1989–1990 and 1991–1992 seasons at Bushland, and the 2000–2001 season at Zhengzhou. Underestimation of ET_o by the Priestley–Taylor equation used by CERES-Wheat (R), and the Jensen–Haise equation, used by ModWht, have also been reported by Gunston and Batchelor (1983), Allen et al. (1989), Steiner et al. (1991), and Howell et al. (1995a). Allen et al. (1989) also indicated that the FAO Penman equation used by CERES-Wheat (P) tended to overestimate ET_o. Recently, Lascano and van Bavel (2007) conclude that current PET and ET calculations cannot satisfy our needs. Results in Fig. 6 are generally consistent with these conclusions.

The underestimation of daily PET or ET_o would seem to be a key reason for underestimated daily ET by MODWht, and during the later part of the growing season by CERES-Wheat (R), especially for days with high evaporative demand. Modification of MODWht's PET module to use the Penman–Monteith equation instead of the Jensen and Haise (1963) equation might increase its applicability

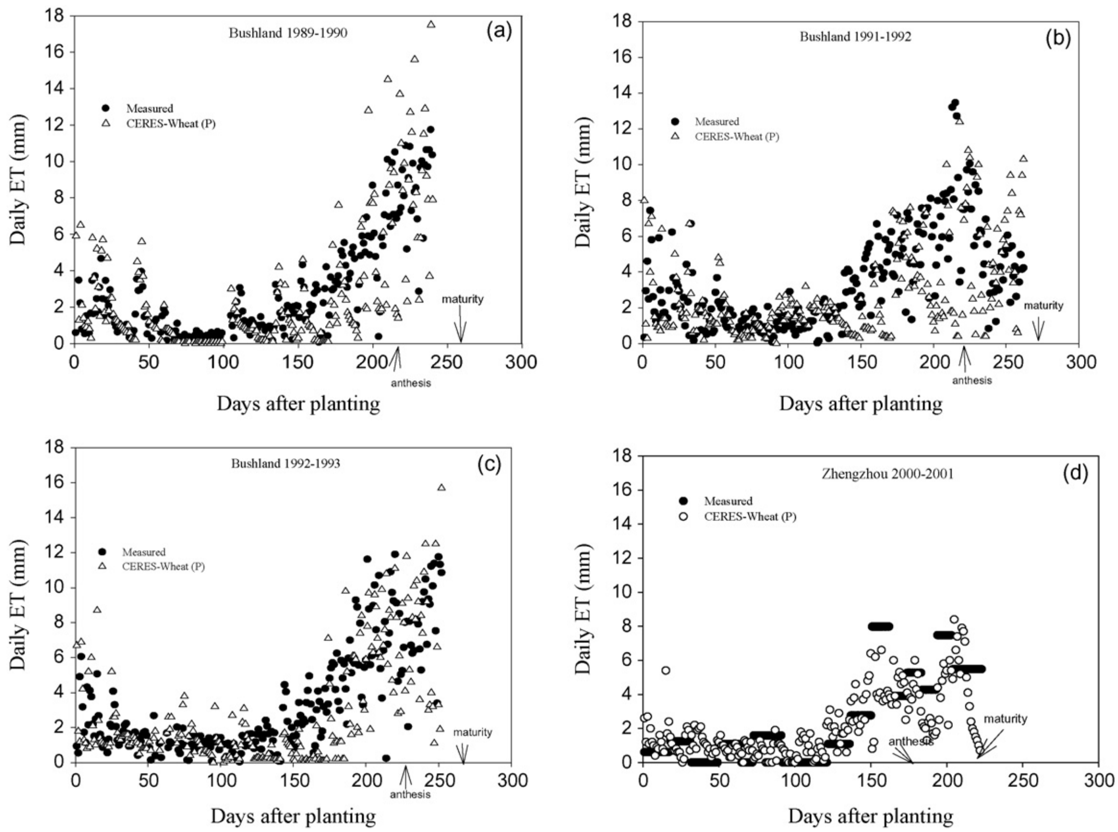

Fig. 5 – Comparison of calculated daily ET by CERES-Wheat (P) using the FAO Penman equation and measured daily ET for the 1989–1990 growing season (a), 1991–1992 growing season (b), 1992–1993 growing season (c) at Bushland, TX, and 2000–2001 growing season (d) at Zhengzhou, China.

to regions outside the inland Pacific Northwest, USA, for which it was originally designed. For CERES-Wheat, the Penman–Monteith equation would appear to be more suitable than either the Priestley–Taylor equation or the Penman equation.

4.4. *Calculation of K_c and LAI*

Daily ET is calculated by CROPWAT simply from Eq. (2). The crop coefficient K_c was intended for conditions in which ''No limitations are placed on crop growth or evapotranspiration from soil water and salinity stress, crop density, pests and diseases, weed infestation or low fertility'' (Allen et al., 1998), and for use in irrigation management and water balance studies. This average crop coefficient is more convenient than using one calculated on a daily time step, for which separate transpiration and evaporation coefficients (K_{cb} and K_e) are recommended (Allen et al., 1998). However, the model CROPWAT does not have this capability.

Published K_c values in Table 12 of Allen et al. (1998) for winter wheat are 0.7 for the initial growth stage, 1.15 for the middle growth stage, and 0.24 for the late growth stage of machine-harvested wheat, or 0.40 for hand-harvested wheat. Measured daily K_c, i.e. measured ET divided by PET calculated by REF-ET, is plotted in Fig. 7 as a function of cumulative growing degree days (CGDD) for all three study years at Bushland, along with a least squares cubic smoothing polynomial. There is clearly a great deal of scatter above and below the fitted curve, with a range of 1.0 or more in measured K_c values. Nonetheless, values along the fitted curve are very similar to those of Allen et al. (1998), despite the fact that those were meant for ''a sub-humid climate with an average daytime minimum relative humidity (RH_{min}) of about 45% and with calm to moderate wind speeds averaging 2 m s^{-1}.'' The Bushland environment is seldom characterized by this description. Therefore, PET equation adaptability and detailed calibrations of its parameters would benefit the improvement of ET calculation in the water balance components of the models.

CERES-Wheat and MODWht calculate ET by calculating plant transpiration and water evaporation from the soil surface separately, then summing them. We do not have experimental data to evaluate transpiration and soil water evaporation components, but both models simulate LAI through routines for leaf appearance and photosynthate partitioning, then use LAI to calculate ET. Photosynthesis and therefore LAI respond to soil water availability via calculation of the soil water balance. MODWht calculates transpiration simply by multiplying PET by a crop coefficient that equals the calculated LAI value by 3 (Eq. (6)). CERES-Wheat, on the other hand, uses LAI to estimate albedo for

Table 5 – Regression analysis of daily ET calculations by CROPWAT (the Penman–Monteith equation), MODWht (the Jensen–Haise equation), CERES-Wheat (R) (The Priestley–Taylor equation), and CERES-Wheat (P) (the Penman equation) for the three growing seasons of winter wheat at Bushland, TX and Zhengzhou, China (n, number of available measured daily ET during the growing season; a (intercept), b (slope) of regression line, respectively; r^2, coefficient of determination; MAD, mean absolute difference; RMSE, root mean square error; D, index of agreement)

Model, location and growing season	n	a	b	r^2	MAD	RMSE	D
CROPWAT							
Bushland							
1989–1990	236	1.6**	0.43**	0.50	1.3	1.9	0.87
1991–1992	245	2.3**	0.22**	0.25	0.8	1.9	0.79
1992–1993	238	1.6**	0.51**	0.52	1.6	2.3	0.79
Zhengzhou							
2000–2001	223	0.4**	0.54**	0.72	1.1	1.8	0.85
Mean				0.50	1.5	2.0	0.82
MODWht							
Bushland							
1989–1990	231	0.5**	0.52**	0.64	1.4	2.2	0.82
1991–1992	257	0.4**	0.64**	0.59	1.4	1.9	0.84
1992–1993	245	0.3*	0.63**	0.61	1.4	2.2	0.84
Zhengzhou							
2000–2001	223	0.2*	0.37**	0.52	1.5	1.9	0.69
Mean				0.59	1.4	2.1	0.80
CERES-Wheat (R)							
Bushland							
1989–1990	240	0.3**	0.61**	0.76	1.5	2.3	0.78
1991–1992	262	0.9**	0.49**	0.52	1.8	2.2	0.57
1992–1993	252	0.7**	0.50**	0.55	1.5	2.1	0.81
Zhengzhou							
2000–2001	223	0.8**	0.43**	0.48	1.2	1.7	0.77
Mean				0.58	1.5	2.1	0.73
CERES-Wheat (P)							
Bushland							
1989–1990	240	0.4*	0.72**	0.47	1.6	2.6	0.82
1991–1992	262	1.2**	0.45**	0.21	1.9	2.7	0.69
1992–1993	252	0.6**	0.64**	0.40	1.9	2.7	0.79
Zhengzhou							
2000–2001	223	0.9**	0.51**	0.47	1.3	1.9	0.80
Mean				0.39	1.7	2.5	0.78

*, ** intercept significantly different from zero or slope significantly different from 1 at the 0.05 and 0.01 probability levels, respectively.

EEQ (Eqs. (8)–(10)) when using the Priestley–Taylor option. Whether using the P or R equation, CERES Wheat uses PET or ET_o to calculate both potential soil water evaporation (Eqs. (11) and (12)) and potential transpiration (Eqs. (13) and (14)). Although LAI was not measured at Zhengzhou, it was for all three seasons at Bushland (Evett et al., 1994; Howell et al. (1996).

MODWht seriously overestimated wheat LAI for most of the growth cycle during all three seasons at Bushland (Fig. 8). Furthermore, it calculated leaf senescence earlier than measured and therefore underestimated LAI during the final ~30 d of all three seasons. The LAI in the MODWht model is directly determined by the phyllochron associated with the cumulative growing degree days, and light and stress factors are not considered (Rickman et al., 1996). At the same time, stress factors such as nutrient and water availability, disease, etc. are ignored when determining the loss of green area due to senescence. The data suggest that, at least for Bushland conditions, MODWht tended to overestimate the rate of development and photosynthesis, perhaps due inadequate phyllochron values, or to ignoring stress effects on senescence.

CERES-Wheat (R) and (P) underestimated LAI during 1989–1990, reaching less than half of the maximum measured value of 4 (Fig. 8). CERES-Wheat (P) also seriously underestimated LAI during most of the 1991–1992 and 1992–1993 seasons. CERES-Wheat also simulates LAI via leaf appearance through a phyllochron value and photosynthetic partitioning, and uses LAI to calculate EOS (Eqs. (11) and (12)) and EOP (Eqs. (13) and (14)). These in turn affect the water balance, and therefore root water absorption and plant stress. Our results suggest CERES-Wheat may have

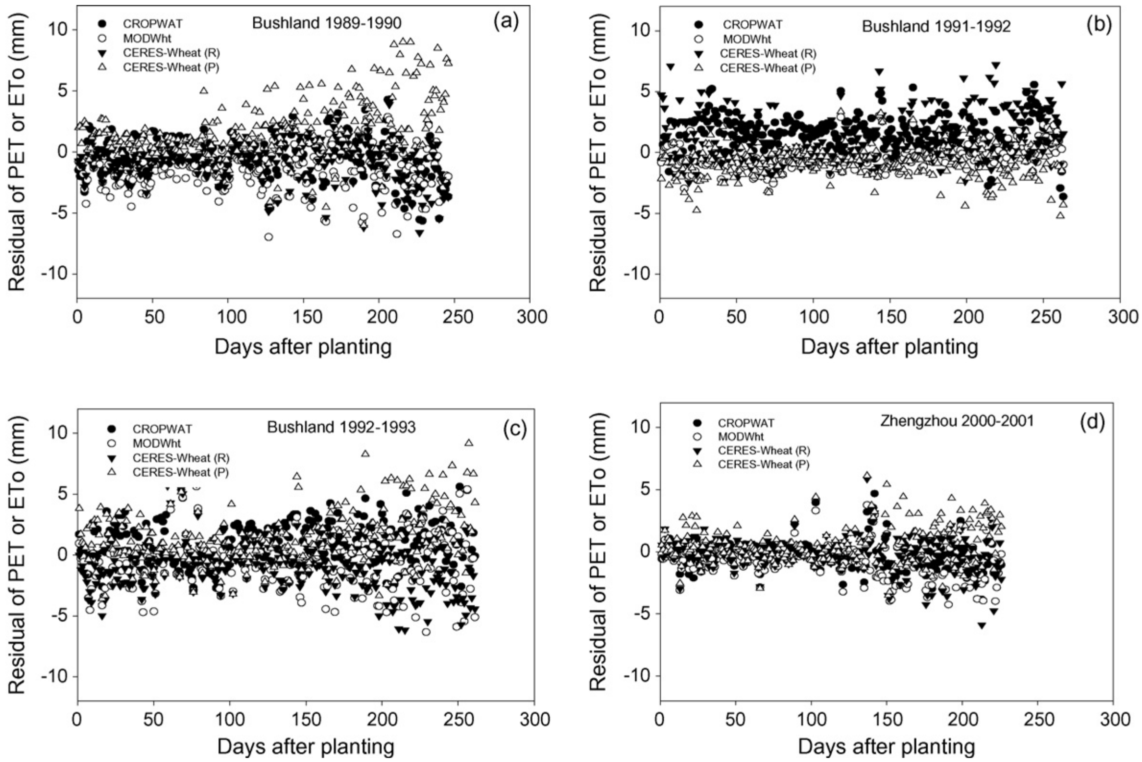

Fig. 6 – Residuals of daily ET_o or PET calculated by CROPWAT using the FAO Penman–Monteith equation, MODWht using the Jensen–Haise equation, CERES-Wheat (R) using the Priestley–Taylor equation and CERES-Wheat (P) using the FAO Penman equation to REF-ET for the growing seasons of 1989–1990 (a), 1991–1992 (b), 1992–1993 (c) at Bushland, TX, and 2000–2001 (d) at Zhengzhou, China.

underestimated photosynthesis, perhaps due to an overestimation of plant stress. CERES-Wheat (R) calculated LAI values that were fairly close to measured ones in the 1991–1992 season, but began to overestimate LAI after 190 DAP in the 1992–1993 season. However, this can be not solved by the calibration of LAI or water stress factors associated parameters because the complex interactions of water balance processes.

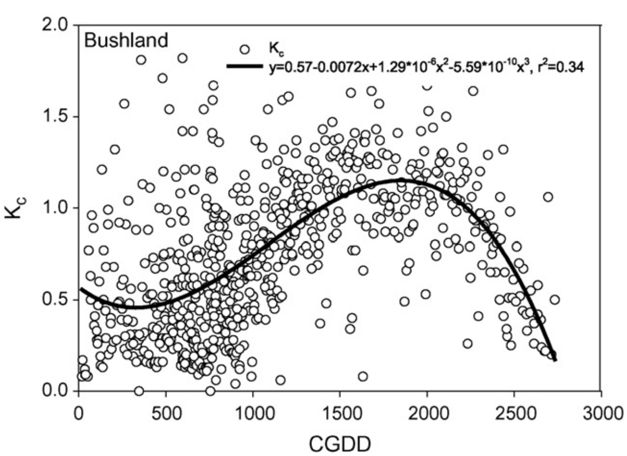

Fig. 7 – Relationship of crop coefficient and cumulative growing degree days (CGDD) of winter wheat during the three growing seasons at Bushland.

5. Summary

We conclude that none of the models could calculate daily ET well at either site. Poor ET calculation appeared to be associated with poor estimations of PET or ET_o, K_c and LAI. The Penman–Monteith equation gave the better estimate of PET, consistent with other studies. CROPWAT generally calculated cumulative ET better than the other models by using K values that were surprisingly consistent with mean measured valued values. Poor simulation of LAI by both MODWht and CERES-Wheat could be to poor simulation of water stress via the water balance and its effect on photosynthesis and LAI development, and at least for MODWht, poor simulation of phenology. Calibration of ET calculation parameters related to K_c and LAI, the water balance, and crop phenology would presumably improve ET calculation of the crop models, but not necessarily increase our understanding of the plant–soil–atmosphere system that drives ET.

Returning to de Wit's (1978) restatement of Occam's razor, and the general principle that model complexity should be geared towards the system the modeler is trying to understand, our general conclusion is similar to those of Evett et al.'s (1995), who were evaluating the mass and energy balance model ENWATBAL (Evett and Lascano, 1993). They found that use of the K_c and PET method was more robust and more precise for 5-day estimates of cumulative ET. The ENWATBAL model gave more precise

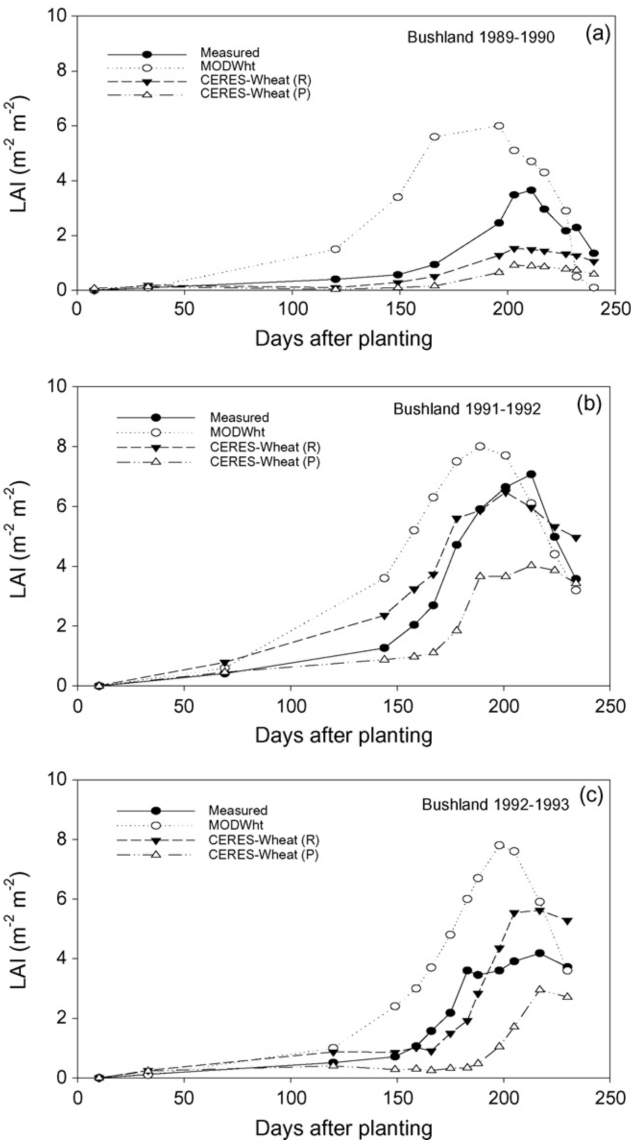

Fig. 8 – Comparison of measured leaf area index (LAI) with calculated LAI with MODWht, CERES-Wheat (R) and CERES-Wheat (P) for the growing seasons of 1989–1990 (a), 1991–1992 (b), 1992–1993 (c) at Bushland, TX.

daily estimates, but it used measured LAI data as an input—in other words, it did not simulate growth or LAI. Neither MODWht nor CERES-Wheat calculated LAI or PET particularly well, indicating there is still room for greater understanding of how plant growth and soil–water interact in the complex field environment, as suggested by de Wit (1978) and others (Pfeil et al., 1992; Moulin and Beckie, 1993; Diekkruger et al., 1995).

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